Beyond the Higgs

new ideas on electroweak symmetry breaking

- Higgs mechanism. The Higgs as a UV moderator of EW interactions. Needs for New Physics beyond the Higgs. Dynamics of EW symmetry breaking
- Review of possible scenarios :Gauge-Higgs Unification, Little Higgs, Composite Higgs, (5D) Higgsless models.

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A decade of experimental successes

- top discovery
- solar and atmospherical neutrino oscillations
- direct CP violation in the K system (d<u>s</u>) (K-long decaying into 2 pions)
- CP violation in the B system (d<u>b</u>)
- evidence of an accelerated phase in the expansion of the Universe
- measure of the dark energy/dark matter composition of the Universe

These results have strengthened the SM as a successful description of Nature ... but

... these experimental results also concluded that there is a physics beyond the Standard Model.

Bounds on (Dangerous) New Physics

Heavy Particles ⇛ new interactions for SM particles

broken symmetry	operators	scaleΛ
B, L	$(QQQL)/\Lambda^2$	10^{13} TeV
flavor (1,2$^{\text{nd}}$ family), CP	$(\bar{d}s\bar{d}s)/\Lambda^2$	1000 TeV
flavor (2,3$^{\text{rd}}$ family)	$m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$	50 TeV

At colliders, it will be difficult to find direct evidence of new physics in these sectors...

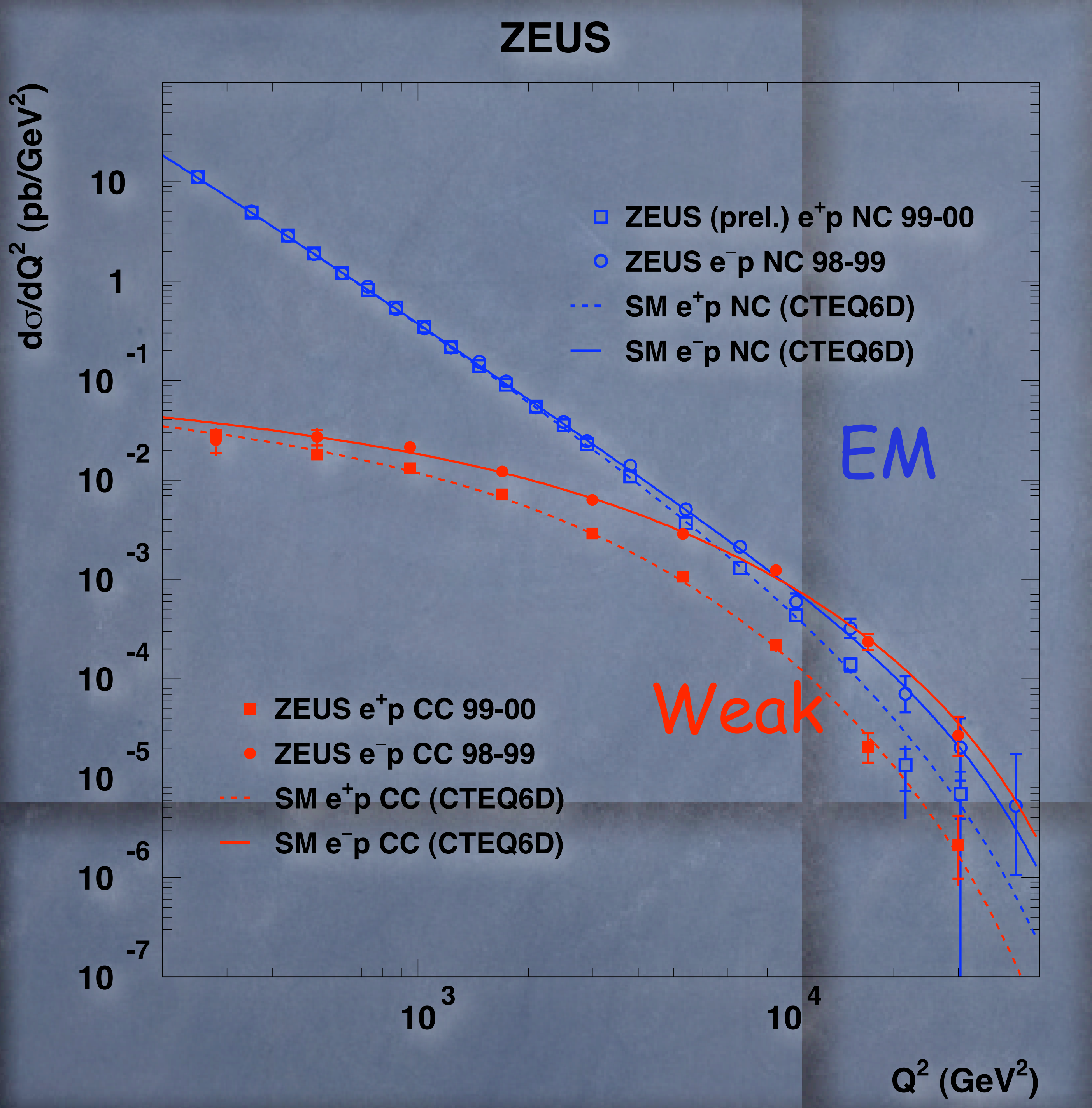
New Physics in the EW sector

$$\left((h^\dagger \sigma^a h) W^a_{\mu\nu} B^{\mu\nu}\right)/\Lambda^2 \qquad |h^\dagger D_\mu h|^2/\Lambda^2 \qquad \left(h^\dagger h\right)^3/\Lambda^2$$

$\Lambda \sim$ few TeV only

high potential for direct detection at LHC, ILC !!!

EW “unification” and EWSB



- Above ~ 100 GeV, electromagnetic and weak interactions are unified
- Below 100 GeV, γ and Z behave differently

$$m_\gamma < 6 \times 10^{-17}\ \mathrm{eV}$$
$$m_{W^\pm} = 80.425 \pm .038\ \mathrm{GeV}$$
$$m_{Z^0} = 91.1876 \pm .0021\ \mathrm{GeV}$$

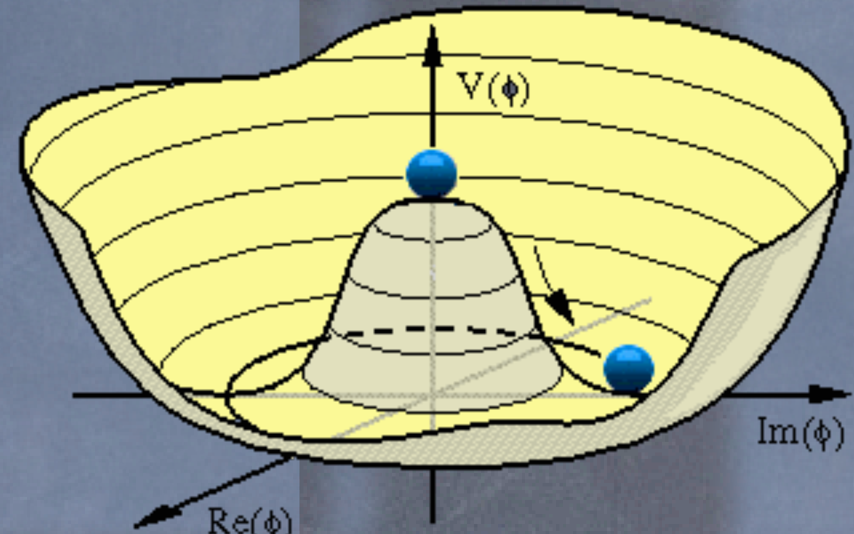
Higgs Mechanism

Symmetry of the Lagrangian

$SU(2)_L \times U(1)_Y$

Higgs Doublet

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$



Symmetry of the Vacuum

$U(1)_{e.m.}$

Vacuum Expectation Value

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \text{with} \quad \mathrm{v} \approx 246 \text{ GeV}$$

$$D_\mu H = \partial_\mu H - \frac{i}{2} \begin{pmatrix} gW^3_\mu + g' B_\mu & \sqrt{2} g W^+_\mu \\ \sqrt{2} g W^-_\mu & -gW^3_\mu + g' B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}^\pm_\mu = \frac{1}{\sqrt{2}} (\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu)$$

$$|D_\mu H|^2 = \tfrac{1}{4} g^2 v^2 \, W^+_\mu W^{-\,\mu} + \tfrac{1}{8} (W^3_\mu \, B_\mu) \begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

- Gauge boson spectrum
  - electrically charged bosons $M_W^2 = \frac{1}{4} g^2 v^2$
  - electrically neutral bosons

$$Z_\mu = c W^3_\mu - s B_\mu$$
$$\gamma_\mu = -s W^3_\mu + c B_\mu$$

Weak mixing angle

$$c = \frac{g}{\sqrt{g^2 + g'^2}} \qquad s = \frac{g'}{\sqrt{g^2 + g'^2}}$$

$$M_Z^2 = \tfrac{1}{4} (g^2 + g'^2) v^2$$

$$M_\gamma = 0$$

Custodial Symmetry

- Rho parameter

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_w} = \frac{\frac{1}{4}g^2 v^2}{\frac{1}{4}(g^2+g'^2)v^2 \frac{g^2}{g^2+g'^2}} = 1$$

- Consequence of an approximate global symmetry of the Higgs sector

$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ Higgs doublet = 4 real scalar fields

$V(H) = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2$ is invariant under the rotation of the four real components

$$SO(4) \sim SU(2)_L \times SU(2)_R$$

$SU(2)_R$

$SU(2)_L$ $\left(i\sigma^2 H^\star \quad H \right) = \Phi$

2x2 matrix

$$\Phi^\dagger \Phi = H^\dagger H \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$V(H) = \frac{\lambda}{4}\left(\mathrm{tr}\Phi^\dagger\Phi - \mathrm{v}^2\right)^2$$

explicitly invariant under $SU(2)_L \times SU(2)_R$

Custodial Symmetry

Higgs vev

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \langle \Phi \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$(W^1_\mu, W^2_\mu, W^3_\mu) \quad \text{transforms as a triplet}$$

$$(Z_\mu\, \gamma_\mu) \begin{pmatrix} M_Z^2 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} Z^\mu \\ \gamma^\mu \end{pmatrix} = (W^3_\mu\, B_\mu) \begin{pmatrix} c^2 M_Z^2 & -csM_Z^2 \\ -csM_Z^2 & s^2 M_Z^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

The $SU(2)_V$ symmetry imposes the same mass term for all W^i thus $c^2 M_Z^2 = M_W^2$

ρ = 1

More generally:

$$\rho = \frac{\sum_i (T_i(T_i+1) - T_{3\,i}^2) v_i^2}{2T_{3\,i}^2 v_i^2}$$

Need doublet (T_i=1/2)
with hypercharge 1/2 (T_{3i}=1/2)
to get ρ = 1

The hypercharge gauge coupling and the Yukawa couplings break the custodial $SU(2)_V$.
The radiative corrections will generate a (small) deviation to ρ = 1 at one loop.

Counting the degrees of freedom

$$SU(2)_l \times U(1)_y \to U(1)_{em}$$

3 broken gauge directions = 3 eaten Goldstone bosons

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

3 eaten Goldstone bosons which become the longitudinal polarizations of the massive gauge bosons

One physical degree of freedom the Higgs boson

$$H = e^{i\pi^a T^a} \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

In the unitary gauge, the π^a are non-physical.

$$V(H) = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2 = \underbrace{\lambda v^2\, h^2}_{\text{mass term}} + \underbrace{\lambda v\, h^3 + \tfrac{1}{4}\lambda\, h^4}_{\text{self-couplings}}$$

Higgs as a UV moderator

Why do we need a Higgs ?

The W and Z masses are inconsistent with the known particle content! Need more particles to soften the UV behavior of massive gauge bosons.

Indeed a massive spin 1 particle has 3 physical polarizations:

$$A_\mu = \epsilon_\mu \; e^{ik_\mu x^\mu}$$

$$\epsilon^\mu \epsilon_\mu = -1 \qquad k^\mu \epsilon_\mu = 0$$

$$k^\mu = (E, 0, 0, k)$$

with $\quad k_\mu k^\mu = E^2 - k^2 = M^2$

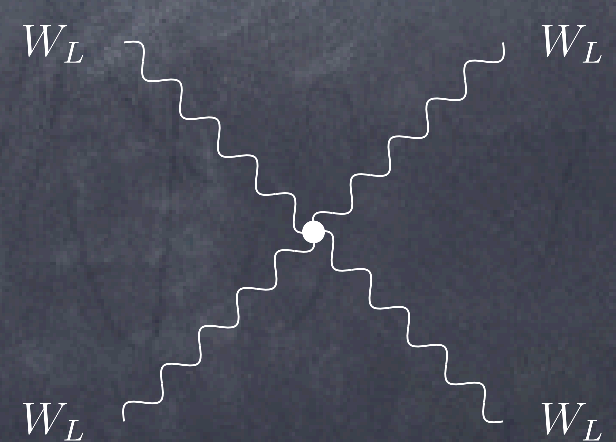
- 2 transverse: $\begin{cases} \epsilon_1^\mu = (0,1,0,0) \\ \epsilon_2^\mu = (0,0,1,0) \end{cases}$

Exercise

- 1 longitudinal: $\epsilon_\perp^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

(in the R-ξ gauge, the time-like polarization ($\epsilon^\mu \epsilon_\mu = 1,\ k^\mu \epsilon_\mu = M$) is arbitrarily massive and decouple)

Bad UV behavior for the scattering of the longitudinal polarizations



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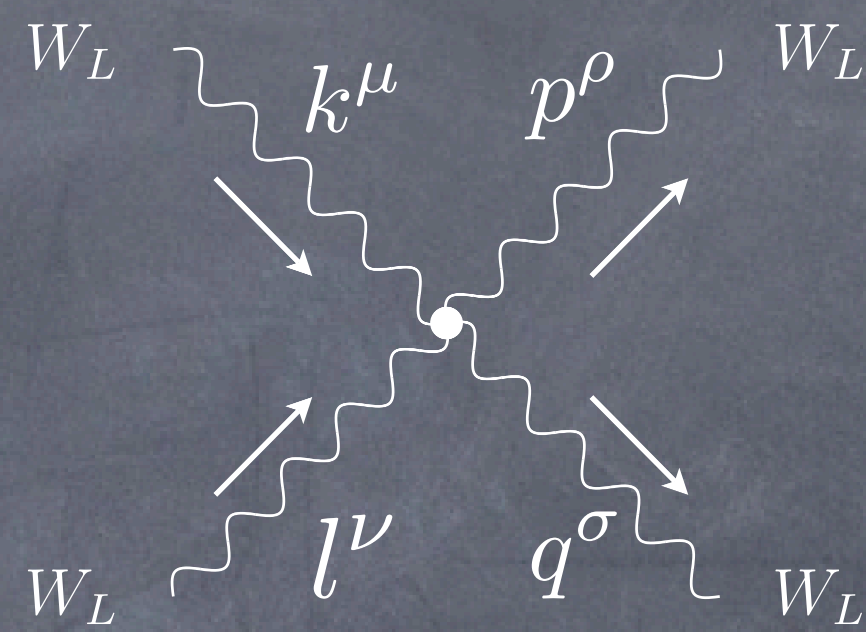
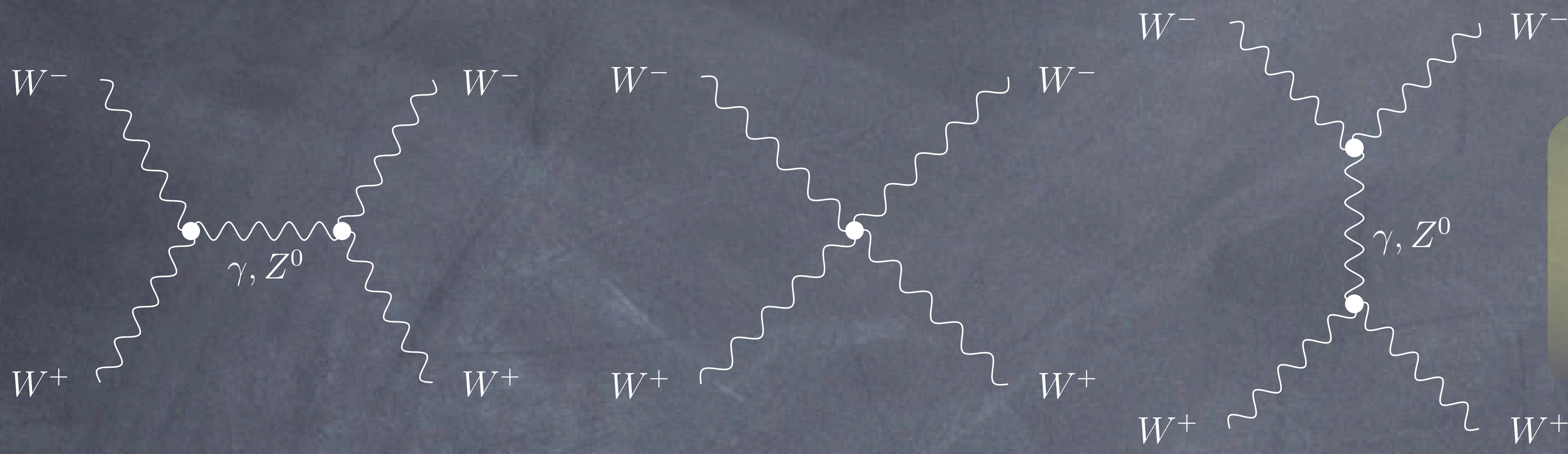


$$\mathcal{A} = \epsilon_l^\mu(k)\epsilon_l^\nu(l)\, ig^2(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho})\, \epsilon_l^\rho(p)\epsilon_l^\sigma(q)$$

$$\mathcal{A} \propto g^2 \frac{E^4}{M^4}$$

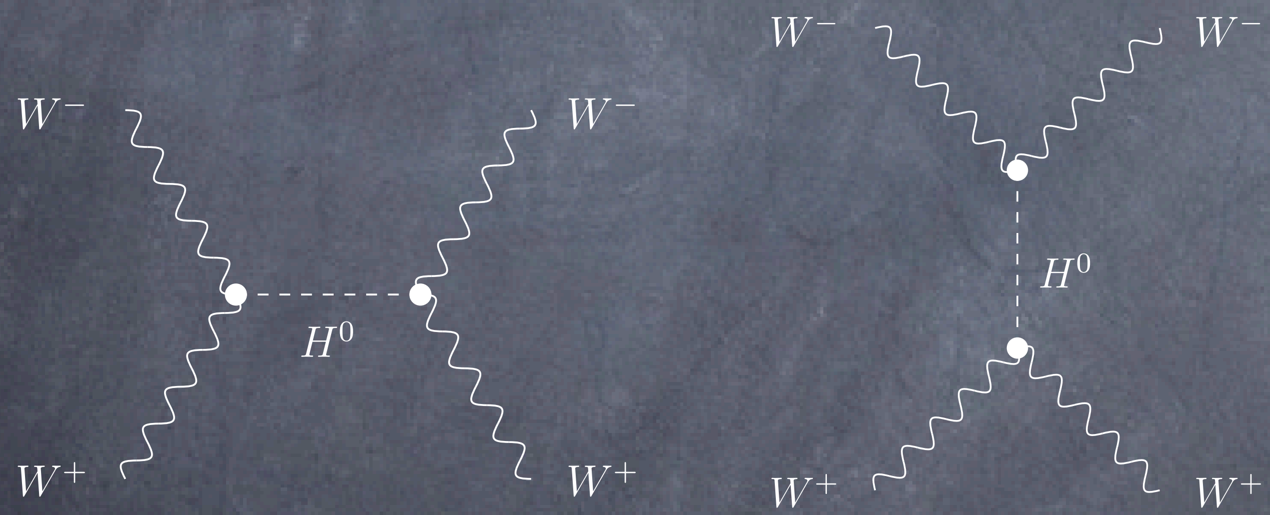
violations of perturbative unitarity around E ~ M

Why do we need a Higgs ?



$$\mathcal{A} = g^2 \left(\frac{E}{M_W} \right)^2$$

+



$$\mathcal{A} = -g^2 \left(\frac{E}{M_W} \right)^2$$

$$\mathcal{A} = g^2 \left(\frac{M_H}{2M_W} \right)^2$$

The Higgs boson unitarize the W scattering
(if its mass is below ~ 700 GeV)

Lewellyn Smith '73
Dicus, Mathur '73
Cornwall, Levin, Tiktopoulos '73

Unitarity Bound

Lee, Quigg, Thacker '77
Chanowitz, Gaillard '85

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\,|\mathcal{A}|^2$$

Partial wave amplitude decomposition:

$$\mathcal{A} = 16\pi \sum_{l=0}^{\infty}(2l+1)P_l(\cos\theta)a_l \qquad a_l = \frac{1}{32\pi}\int_{-1}^{1} d(\cos\theta)P_l(\cos\theta)\mathcal{A}$$

$P_0(x) = 1, P_1(x) = x, P_2(x) = 3x^2/2 - 1/2\ldots$

$$\sigma = \frac{16}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2$$

Optical theorem:

$$\sigma = \frac{1}{s}\,\mathrm{Im}\left(\mathcal{A}(\theta=0)\right) \Rightarrow \mathrm{Im}\,(a_l) = |a_l|^2 \Rightarrow \left(\mathrm{Im}\,(a_l) - 1/2\right)^2 + \left(\mathrm{Re}\,(a_l)\right)^2 = 1/4$$

$$|\mathrm{Re}\,(a_l)\,| \leq 1/2$$

SM witout a Higgs $\quad a_0 = \dfrac{g^2E^2}{16\pi\, M_W^2} \Rightarrow E \leq 620\ \mathrm{GeV}$

SM with a Higgs $\quad a_0 = \dfrac{g^2M_H^2}{64\pi\, M_W^2} \Rightarrow M_H \leq 1.2\ \mathrm{TeV}$

Stronger Bound
$2W^+W^- + ZZ$ scattering
$M_H \leq 780\ \mathrm{GeV}$

Physics Beyond the Higgs?

Is the Standard Model with a Higgs a UV finite theory?
i.e. valid to arbitrarily high energies

Of course, the SM will fail around the Planck scale

but the real question is

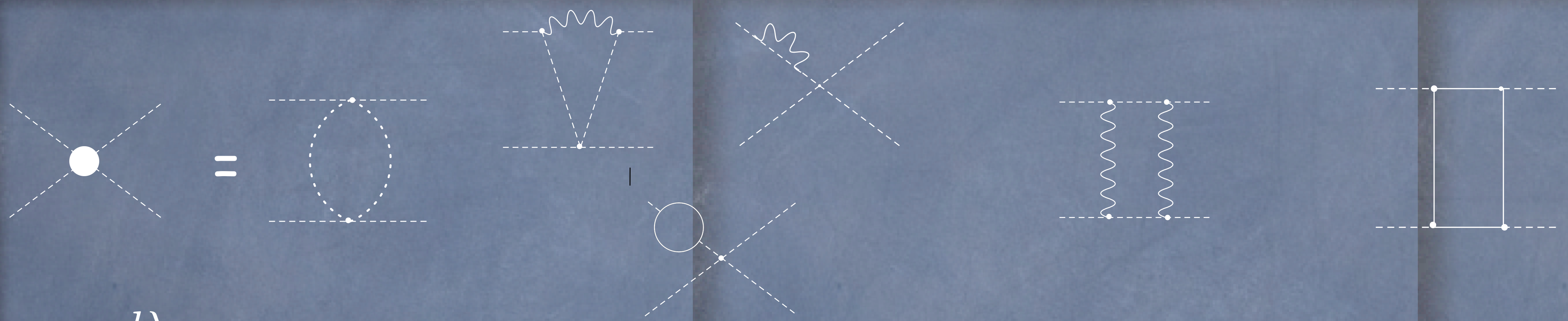
Is there any reason to think there is new physics
between the weak scale and the Planck scale?

Quantum corrections of the Higgs potential

Quantum Behavior of the Higgs^4 Coupling (I)

$$V(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$

$vev : v^2 = \mu^2/\lambda$ $\qquad$ $\mathrm{mass} \;\; : m_H^2 = 2\lambda v^2$



$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$

Higher loops
Small Yukawa

Large mass (λ dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2$$

λ increases with Q: IR-free coupling

$$\lambda(Q) = \frac{m_H^2}{2v^2 - \frac{3}{2\pi^2} m_H^2 \ln(Q/v)}$$

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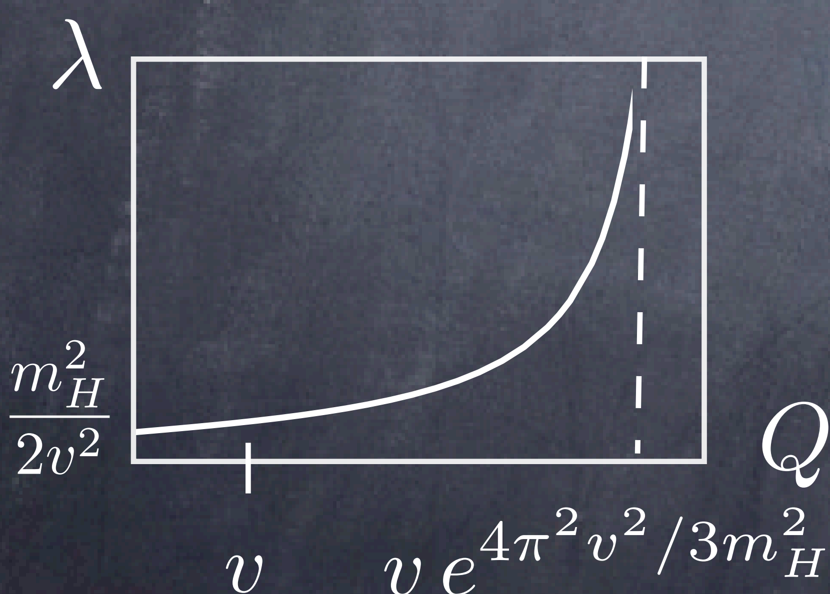
Large mass (λ dominated RGE)

$$\lambda(Q) = \frac{m_H^2}{2v^2 - \frac{3}{2\pi^2} m_H^2 \ln(Q/v)}$$

Landau pole



$$\Lambda \le v\, e^{4\pi^2 v^2/3m_H^2}$$

New physics should appear before that point to restore stability

for m_H fixed, upper bound on Λ
for Λ fixed, upper bound on m_H

No microscopic description: for $\Lambda \to \infty$, trivial theory (λ=0)

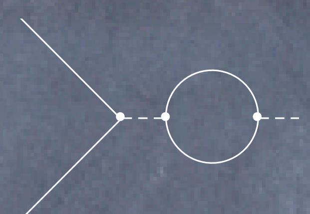
Quantum Behavior of the Higgs^4 Coupling (II)

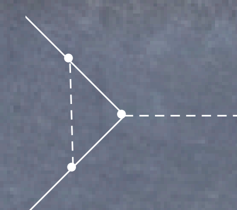
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

Small mass (y_t dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = -6y_t^4$$

λ decreases with Q.





$$\left(16\pi^2 \frac{dy_t}{d\ln Q} = \frac{9}{2}\, y_t^3 + \right.$$ Higher loops Small Yukawa $$\left. y^2(Q) = \frac{y^2(Q_0)}{1 - \frac{9}{16\pi^2} y^2(Q_0) \ln \frac{Q}{Q_0}} \right)$$

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

$2\pi^2 m_H^2/3y_t^4 v^2$

Quantum Behavior of the Higgs^4 Coupling (II)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 + \text{Higher loops Small Yukawa}$$

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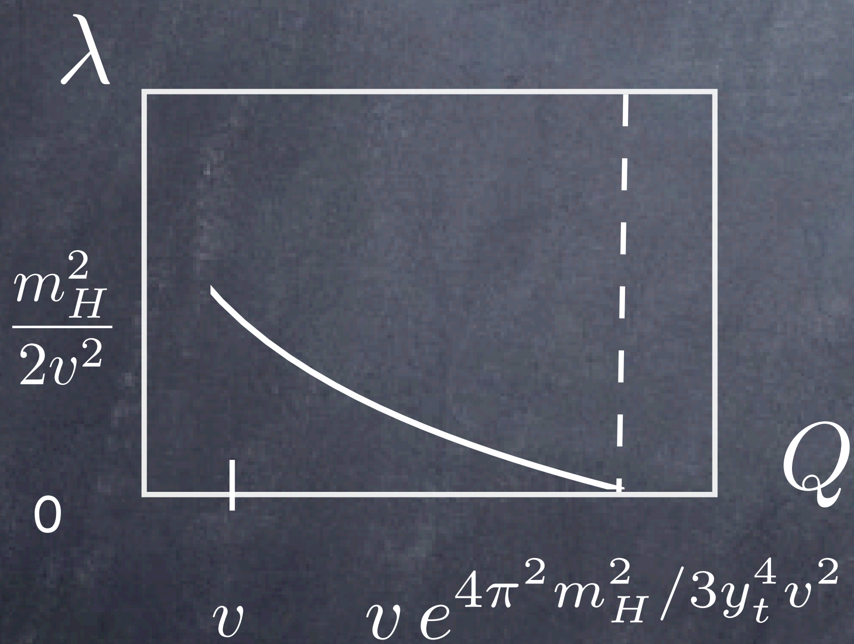
$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln\frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln\frac{Q}{Q_0}}$$



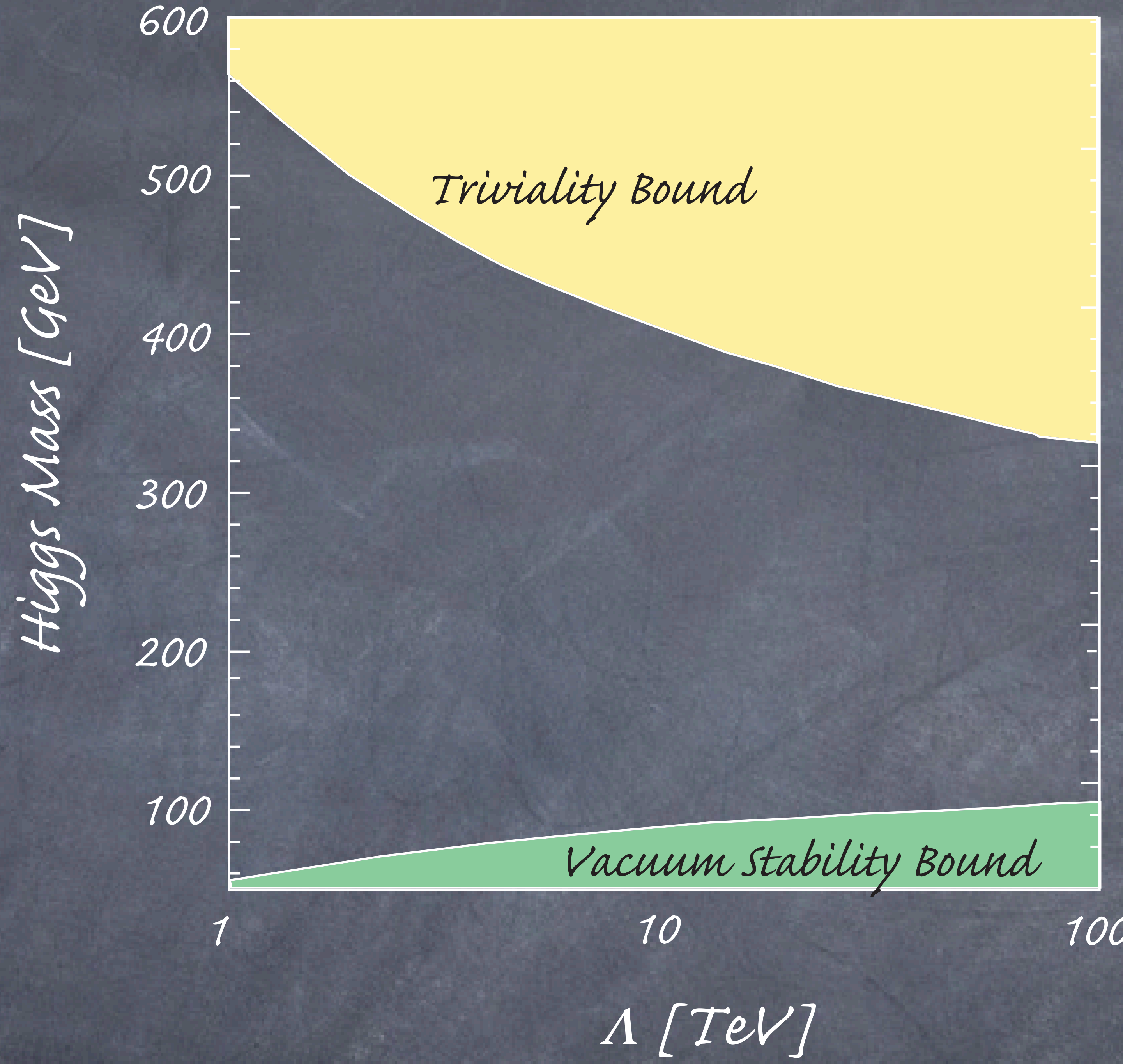
$\lambda < 0$ ⇛ potential unbounded from below

$\lambda(Q) = 0$ for $\lambda_0 \approx \frac{3}{8\pi^2} y_0^4 \ln\frac{Q}{Q_0}$

New physics should appear before that point to restore stability

$$\Lambda \leq v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

for Λ fixed, lower bound on m_H



the SM is not UV complete

it is an effective theory of a more comprehensive theory

the cutoff of the SM can be rather low

Solution to the Higgs^4 Coupling Instabilities

find a symmetry such that

$$\boxed{\lambda \equiv g^2}$$

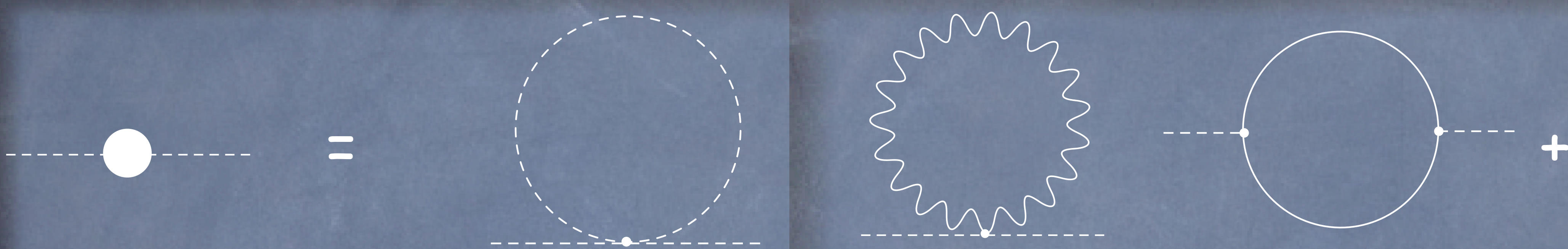
the Higgs quartic will inherit the good UV asymptotically free behavior of the gauge coupling

Examples of such symmetry:

- supersymmetry
- gauge-Higgs unification: the Higgs is identified as a component of the gauge field along some extra-dimensions.

Quantum Instability of the Higgs Mass

so far we looked only at the RG evolution of the Higgs quartic coupling (dimensionless parameter). The Higgs mass has a totally different behavior: it is higly dependent on the UV physics, which leads to the so called hierarchy and little hierarchy problems.



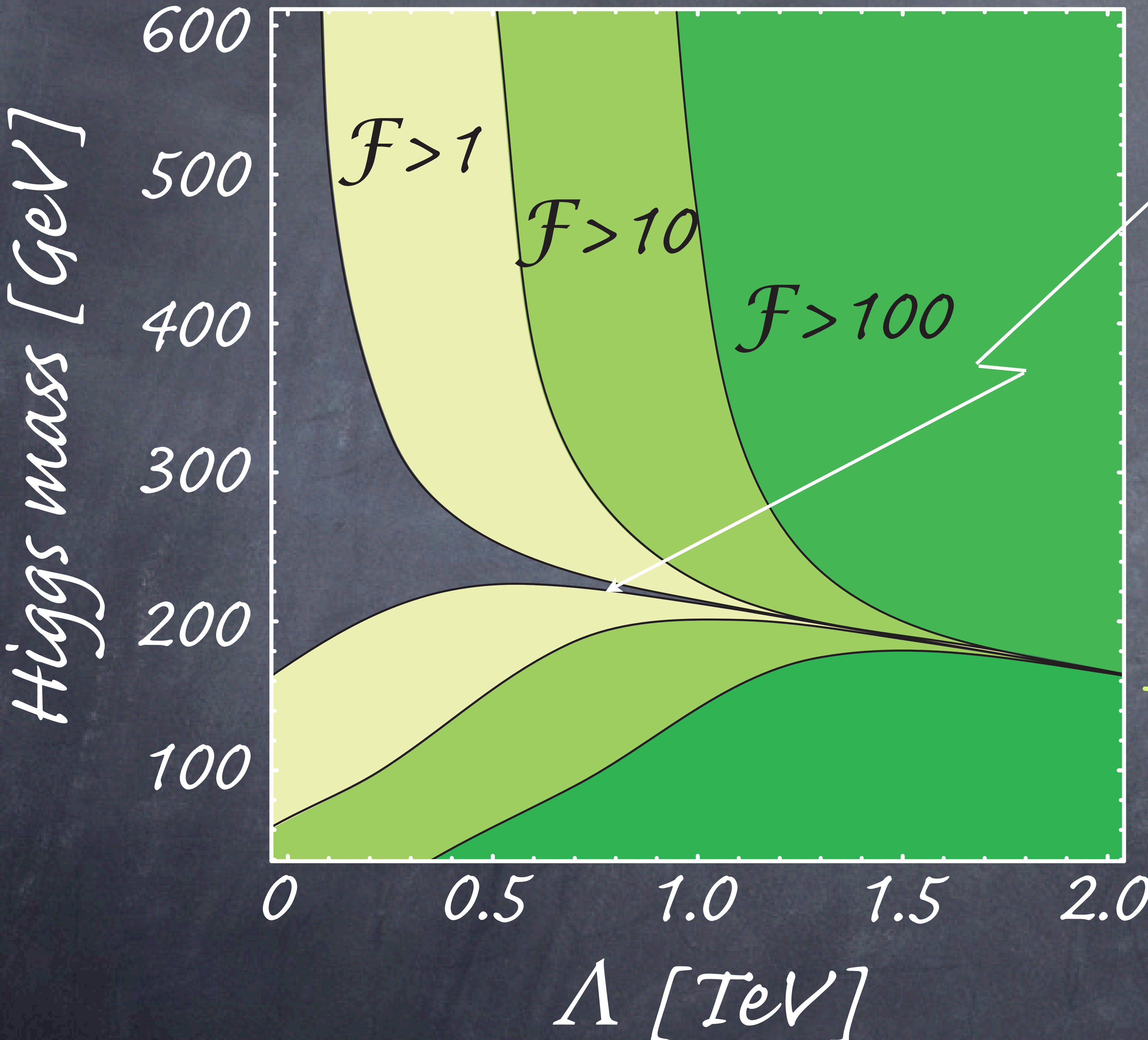
Higher loops
Smaller Yukawa

$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{(k^2 - m^2)^2} \propto \Lambda^2$$

$$\boxed{m_H^2 \sim m_0^2 - (115 \text{ GeV})^2 \left(\frac{\Lambda}{400 \text{ GeV}} \right)^2}$$

A low-mass Higgs boson is imperiled by quantum corrections.

The hierarchy problem is a technical problem in scalar theories at two loop



Veltman's throat

$$m_H^2 = 4m_t^2 - 2m_W^2 - m_Z^2 \approx (320\ \mathrm{GeV})^2$$

(one-loop)

The throat actually
closes up at higher loops

shouldn't be taken seriously:
in absence of any symmetry,
there is no reason to use the
same cutof for all particles

Kolda, Murayama '00

Symmetries for a natural EWSB

How to Stabilize the Higgs Potential

Goldstone's Theorem

spontaneously broken global symmetry $\Rightarrow$ massless scalar

... but the Higgs has sizable non-derivative couplings

The spin trick

a particle of spin s: 2s+1 polarization states

...with the only exception of a particle moving at the speed of light

... fewer polarization states

Spin 1 Gauge invariance $\longrightarrow$ no longitudinal polarization $\searrow$ m=0

Spin 1/2 Chiral symmetry $\longrightarrow$ only one helicity $\nearrow$

... but the Higgs is a spin 0 particle

Symmetries to Stabilize a Scalar Potential

Supersymmetry

fermion ~ boson

Higher Dimensional
Lorentz invariance

$$A_\mu \sim A_5$$

4D spin 1   4D spin 0

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

Other symmetries?

Ghost symmetry

[Grinstein, O'Connell, Wise '07]

SM particle ~ ghost

It was known since Pauli-Villars that ghosts can soften the UV behavior of the propagators. But they are unstable per se.

Lee-Wick in the 60's proposed a trick to stabilize the ghosts (at the price of a violation of causality at the microscopic scale).

Conclusions

EW interactions need a UV moderator
to unitarize WW scattering amplitude

the SM with a light fundamental scalar cannot be (naturally)
extended to very high energies

new particles/symmetries are expected to populate the TeV scale
to trigger the breaking of the EW symmetry